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Design of the Ballistic Missile Defense System Hardware-in-the-Loop

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Test and evaluation (T&E) of geographically dispersed integrated systems are severely constrained by cost, range safety restrictions, and ability to test while in an operational state. The Missile Defense Agency has embarked on a hardware-in-the-loop (HWIL) framework development that has the capability to characterize the performance of the Ballistic Missile Defense System by integrating the operational software in a distributed laboratory architecture. The HWIL framework is also intended to test the operational assets in their fielded configuration and location. As more advanced radar discrimination algorithms are developed, testing these algorithms and determining the impact on the system performance becomes increasingly more difficult. The ability to stimulate radar signal processors with synthetic signatures has also advanced over the last few years, thus enabling greater opportunity for testing. The integration of separate defense programs, and thus independently developed HWILs, has been a concern for the agency. The development of the Ballistic Missile Defense System HWIL will provide the agency with a unified architecture across all Missile Defense Agency programs, allowing consistent threat and environmental effects across all systems.

Key words: accreditation; advanced test facilities; complex operational systems; integrated network; realistic mission environments; simulator/stimulator testing labs; verification & validation.

Using the Ballistic Missile Defense System (BMDS) as an example, this article articulates the Missile Defense Agency's (MDA) hardware-in-the-loop (HWIL) framework design and development for testing the BMDS. This framework will allow MDA to establish a degree of confidence in the expected performance of a very complex operational system that cannot be evaluated by conventional tests. The inherent difficulty in executing an operational test in the conventional sense presents the Operational Test and Missile Defense Agencies with challenges to field such a complex system.

This article examines the benefits and challenges of implementing a distributed HWIL framework and articulates areas that are critical in design, implementation, and execution of the BMDS HWIL. In addition, the framework test and control functions, communication architecture, and interface requirements are discussed. Topics include

- BMDS components
- BMDS HWIL fidelity requirements
- Challenges of distributed simulation execution, including data latency, data rates, and synchronization
- Management and coordination of complex test requirements
- Common threat and environment for stimulation of simulation elements
- Methods for HWIL verification, validation, and accreditation.

The ballistic missile defense system

The BMDS Program is designed to provide protection against limited ballistic missile attacks targeted at the United States. The MDA mission is to develop, test, and field this missile defense system. Using complementary interceptors; land-, sea-, air-, and space-based sensors; and battle management

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command and control systems, the planned missile defense system will be able to engage all classes and ranges of ballistic missile threats. All ballistic missiles share a fundamental characteristic—they follow a trajectory, which includes three phases: boost, midcourse, and terminal. By fielding a layered defense system and attacking the missile in all phases of flight, MDA can exploit opportunities to increase the effectiveness of missile defenses and complicate an aggressor's plans. The MDA has connected several test ranges to form the BMDS Test Bed, which will add realism to ground- and sea-based midcourse testing by allowing multiple engagements and different trajectories and adding additional intercept areas. The BMDS Test Bed also includes boost and terminal segment tests, which will demonstrate the viability of the layered missile defense concept.

The potential boost-phase defense elements are high-power Air-Borne Lasers and kinetic energy systems. The primary elements in the midcourse phase are the Aegis Ballistic Missile Defense and the Ground-based Midcourse Defense (GMD). The terminal elements are the Theater High Altitude Area Defense (THAAD) and the Patriot Advanced Capability 3 (PAC-3). Other elements include the experimental Space Tracking and Surveillance System along with its strategic and theater mission controller, the Command & Control Battle Manager and Communication system, and other agency experimental and operational sensors.

The test and evaluation challenge

Classical test and evaluation (T&E) of a new weapon system entails repeated live "firings" by forces that would be employing the system against the expected threats in an environment similar, if not identical, to the expected battle space. Although the BMDS Test Bed provides for more realistic operational testing and capability assessments, only a limited number of flight tests will be conducted. In support of system assessment activities, the T&E community will use flight test, digital simulation, and HWIL simulation data.

The BMDS HWIL framework provides a means to test the BMDS operational software in a controlled laboratory environment. The HWIL framework is also intended to test the operational assets at their fielded sites and host country. As new advanced radar algorithms are developed, the need to inject threat stimuli directly into the signal processor hardware increases. As much as possible, the architecture incorporates the component operational processing hardware and software that will be used in the field, implementing the "Test What You Fly, Fly What You Test" paradigm.

As the BMDS Block upgrades are developed, the impact on system-level performance must be determined. The HWIL framework will allow MDA management to evaluate the upgrades before fielding.

The MDA is requiring the BMDS HWIL to support BMDS system-level performance-based assessments and support BMDS system-level concurrent test training and operations functions. The HWIL framework will allow simultaneous execution of engagement sequence groups; testing both theater and strategic assets. MDA can use test data to assess interoperability of MDA elements, demonstrate the Command & Control Battle Manager and Communication system capability to control and manage BMDS communication networks, sensor management, and display situational awareness to the warfighter.

The Operational Test Agency also uses this test data to characterize BMDS operational capability, which includes threat detection, tracking, discrimination, engage, intercept, and destroy. Other objectives include characterization of information exchange capabilities among BMDS elements. The warfighter additionally wants to verify courses of action, tactics, techniques, and procedures.

Benefits to HWIL testing

With the complexity of the BMDS, integrating multiple systems into a joint fighting force is a challenge. Each element is a completely different acquisition and each has somewhat different requirements. Being separate, each element does not know exactly what dependencies and needs it requires for interoperability with the other elements. Independent testing and verification of the elements does not necessarily fully verify the BMDS or fully assess the system capabilities. If, for instance, the boost-phase elements cannot destroy the threat, their tracking data could be used to enable the midcourse battle-manager to use earlier and more accurate data to cue the midcourse element radars. The benefits of the BMDS HWIL are to help in flight test planning, interoperability, and performance assessment.

Flight test planning includes development of flight test concept of operations, timeline analysis for the mission director, determination of when to filter or include range radar track reports, evaluation of the exclusion of test range assets, pre-mission testing, verification of element interfaces, predicting the probability of mission success, and testing of off-nominal excursions.

The BMDS HWIL may also be instrumental in the design and development of the BMDS Battle Manag-

er, which will have to interface with all element battle management systems. Areas of interest include message translation, message traffic analysis, situational awareness, allocation of interceptors, track correlation, search cueing, drop track reasoning, estimates of sensor covariance, and hand-over strategies between sensors of different elements during different engagement phases.

The most critical benefit is determining system capability and testing of block upgrades. The results of HWIL testing can be used to demonstrate and verify that system requirements are met. Analysis efforts include system capability assessment, kill vehicle and sensor acquisition, tracking and discrimination, and system battle-space evaluation.

HWIL description

This article provides a construct for implementation of a BMDS HWIL and is defined to include as much as possible the tactical hardware and software. HWIL facilities consist of space-based and radar sensors, interceptors, and battle management and communications. Obviously the radar antenna and the interceptor booster cannot be implemented in their entirety. Typically, the radar HWIL consists of the data processors and, in some instances, the signal processors. The interceptor HWIL usually consists of the data processors, which execute the guidance software and the software utilized to process the seeker imagery and determine the interceptor's acquisition, tracking, and discrimination performance. Typically the Battle Manager is represented by the actual tactical hardware and software, with the communication interfaces and simulated delays and timing.

The BMDS HWIL will integrate laboratory facilities in locations across the United States and integrate the fielded operational assets, including those in other countries and at sea. The BMDS HWIL will contain a network to transmit simulation truth data to the elements; a tactical communication network is also available to exercise and evaluate the real communication between elements. The simulation network uses the simulation protocol messages, while the tactical network uses satellite and fiber-optic links, with a variety of tactical message types.

The development of the BMDS HWIL framework will provide the agency with a unified architecture across all MDA programs, allowing consistent hardware, environment, and threat stimulation. Commonality is needed in order to reduce risk. The benefits to achieving commonality in the target generator include:

- Ensuring confidence and control of target data—"Single Source of Models."
- Ensuring consistent target representation across multiple elements—"ALL right or ALL wrong."
- Minimizing the difference in performance between elements—"Level Playing Field."
- Reducing development/modification cost and schedule—"One Time Fix."
- Reducing cost and schedule for element project offices (provides elements with HW/SW to drive stand-alone element testing/verification).
- Reducing target & environmental model verification & validation (V&V) cost and schedule.
- Maximizing reuse of target development efforts and code.
- Reducing risk of interpretation.
- Maximizing configuration control.
- Providing linkage and heritage between elements.

Depending on whether the test is for interoperability or performance verification significantly drives the fidelity and commonality of the target generator.

HWIL framework. The fidelity of the simulation representations can vary across different programs; however, the BMDS system engineer and integrator must determine the fidelity of the configuration needed based on the requirements and intended use of the simulation output data.

The element representations should at a minimum have the operational software integrated into the simulation or hosted on the actual tactical data processor hardware. In addition, the signal processor could be added, along with the missile HWIL, and in-band injection of scenes to the sensor.

The basic BMDS HWIL architecture will consist of the test, execution, and control (TEC) module, the Test Interface Unit, and the element HWIL representations.

Test, execution, & control (TEC). The importance of the TEC module is to establish the connectivity and determine the particular test cases and setup required. The TEC module must synchronize all participants' simulation time and provide the necessary initialization and start commands to each representation. The TEC module also provides updated interceptor state information from each element to the other elements participating in the exercise.

The TEC conducts three major functions: pre-mission, mission, and post-mission execution. In general, the BMDS HWIL pre-mission TEC provides single point control in defining test cases and providing the capability to specify test simulation start time (past, present, future).

During the actual test event execution, the BMDS HWIL mission TEC provides displays that summarize BMDS HWIL framework and element health and

status, situational awareness of BMDS elements under test (element positions, sensor coverage, and threat), and framework and system events for monitoring. BMDS HWIL mission TEC also provides the capability to monitor and display run-time test integrity metrics to include framework and tactical message traffic, message latency, and loss.

After completion of the test case, the BMDS HWIL post-mission TEC provides the capability to import raw and/or processed data to a centralized database management system. This data will be provided to the MDA and Operational Test Agency (OTA) communities for analysis.

Test interface unit. Another critical piece of any HWIL is the target generator module. The test interface unit comprises modules to generate threat trajectories and dynamics, radar signatures, threat plume intensities, and interceptor signatures. In conjunction, common environmental libraries are utilized to induce effects to the signatures. The environmental effects include ionosphere, earth limb, refraction, attenuation due to standard atmosphere, and rain. Other celestial objects modeled include satellites, the sun, and the moon. Interceptor debris is also modeled. The resultant signatures are then provided to the component representations.

As more advanced radar discrimination algorithms are developed, testing these algorithms and determining the impact on the system performance has become increasingly more difficult. The ability to stimulate radar signal processors with synthetic signatures has also advanced over the last few years, thus enabling greater opportunity for testing. The test interface unit will have the ability to drive both the data processor and the signal processor to minimize the cost impacts of replacing all element representations.

Having a distributed, HWIL simulation architecture only amplifies the need for adequate timing analysis. Bandwidth often limits the data rates between facilities and elements. The HWIL system architectural engineer must determine the data rates at each level of the simulation from the TEC, to the target generator, to the element interface, and even the rates associated with tactical communications between the elements. A test interface unit will be co-located with each component to minimize data latency. Each component will have to have an element-specific interface to incorporate the different radar waveforms and integration rates needed.

MDA test events

The MDA has embarked on a test campaign for each year and block upgrade. The campaign consists of laboratory testing and operational asset testing.

Ground Test–Integrated (GTI) will be a distributed laboratory system-level test, utilizing MDA element HWIL facilities. The purpose of the test is to demonstrate the performance capability of the BMDS. The GTI will provide data for element and system-level assessments by executing a variety of scenarios and conditions, and evaluating sequences of events from the BMDS kill chain (e.g., detection, tracking, engagement, etc.).

Ground Test–Distributed (GTD) will be a distributed fielded system-level test. Each BMDS element has incorporated into the tactical operational software the ability to execute simulated tests, similar to the HWIL laboratories. The major difference between the GTD and GTI is that the GTD will exercise the tactical communication links from the actual fielded locations. In general, the test cases in the GTD are a subset of the GTI. The GTD is a progression of the GTI testing. GTD are intended to double check that the performance of the operational assets replicate the performance evaluated during the GTI test campaign.

The concurrent test training and operations concept will capitalize on the GTD architecture to allow the warfighter the opportunity to train and test on the operational assets, while maintaining operational capability to defend the nation. This concept will increase the requirements on both the HWIL framework and the operational system. However, the benefits to the warfighter to train while on station will significantly increase troop efficiency. The crews will be able to evaluate their tactics, techniques, and procedures and the command structure communications.

Evaluation

The test requirements process is a large and complex job. The challenge of writing good test requirements can be lessened if the flow down process is used to define overall objectives and operational scenarios. These will flow down to the system requirements, which will flow down to the subsystem requirements, and so on down to the test requirements. Simultaneously while developing a flow down process for the requirements, each requirement must be verifiable and able to fit into specifications. Good test requirements will be very specific and reflect the functionality of the components and, in turn, the system.

The primary objective of any evaluation activity is to determine if the test objectives and requirements have been met. This requires that any observed or potential system performance shortfalls be identified. A comprehensive set of system performance measurements, applied on a per-run basis is used to verify that system performance is maintained within established margins.

These margins define the limits of system performance relative to ensuring successful test implementation.

During each test case run, the critical mission timeline and the expected results for key system events will be documented on the test case run log for each test case. As the test case run is completed, the test director will indicate on the log sheet if the key system events occurred as predicted and if the expected results were obtained. All test case anomalies will be recorded on the test case run log and will be provided to the personnel performing the analysis. After the test case runs are completed, a post-test analysis will be performed. The analysis determines if the mission objectives were met and what the system performance margins are relative to the requirements. In the event of an anomaly, further analysis will be performed on the test case to determine the root cause of the problem and to provide a resolution. A daily assessment report summarizes the information collected during the post-test data analysis activities.

At the completion of the test, the evaluation team will produce a test evaluation report. The contents of this report will include a comprehensive evaluation and analysis of all test objectives and test requirements along with the system level assessment. The results will be made available to the BMDS systems engineer who, in turn, directs future development to improve performance and capability.

HWIL integration and accreditation process

There are four phases in an HWIL integration and accreditation process. The first phase is the delivery of element representations and their stand-alone, checkout testing. During this phase, it is the responsibility of the element integrated process team to deliver V&V data certifying that the model is a valid representation of the element within specified limitations and usage constraints. The second phase is the integration of the element representations into the BMDS HWIL framework, in accordance with jointly defined integration plans. Both the framework and element representations verify the interface control documents have been met.

The third phase includes two distinct activities: (a) element-to-element integration buildup, and (b) test readiness. The integration buildup part of this phase includes testing each element with system Battle Manager and then testing with all elements scheduled to participate in the HWIL configuration. After integration buildup, test readiness activities are conducted including regression testing, dry run execution, and finally lock-down of the HWIL configuration baseline.

All anomalies found during integration, regression, and engineering tests will be documented in Test Incident Reports (TIR). Each TIR will be isolated to an operator, framework, or element issue. The TIR is a management process used for documenting, disposition, and tracking test incidents for future development throughout the testing life cycle.

The output of phase 3 is a signed certification letter from each participating element stating their respective element has been successfully integrated into the HWIL in compliance with the Interface Control Document and can support the test objectives and test requirements. Collectively, the MDA and BMDS elements are executing an ongoing suite of V&V activities to establish the credibility of the element test articles. Each element program manager is responsible for reviewing the V&V data and the integration testing results, after which caveats and limitations are generated. This recommendation is to be delivered to the accreditation agent at the Preliminary Test Readiness Review (PTRR).

The fourth phase is the accreditation of the integrated HWIL test configuration. During this phase, the accreditation agent produces an acceptability assessment and accreditation recommendation, which is provided to the MDA directors of systems engineering and test and evaluation. The directors evaluate the accreditation recommendation and determine if the configuration is ready for test. A signed accreditation letter is then prepared and presented at the Test Readiness Review, which allows the formal start of test execution.

Inherent in this proposed accreditation paradigm is the execution with due diligence of commonly accepted modeling and simulation (M&S) V&V practices.

Verification and validation (V & V)

Verification is the evidence of compliance with requirements for a system (i.e., "Did I build it right?"). Simulation verification is confirmation that all data inputs, logic, calculations, and engineering representations within the simulation accurately portray the intended characteristics and interactions. Validation is the evidence of the system successfully achieving its intended purpose, or function (i.e., "Did I build the right thing?") Validation confirms that a simulation reflects real world expectations and is generally accomplished by comparing simulation results to actual flight test results or other external data. V & V should be implemented in the initial stages of the HWIL development and followed throughout its life cycle.

Failure to plan for proper V&V activities can lead to costly design and schedule ramifications. A clear process for the flow-down of accreditation needs into V&V data products and findings is required. The specific V&V activities identified for execution and the resultant V&V

documentation is explicitly identified in a formal V&V plan. All V&V activities should be selected for execution with the goal of satisfying the fundamental data needed to support an accreditation decision.

Caveats and limitations

A key feature of any accreditation decision is the identification of the caveats and limitations associated with the simulation configuration. Caveats caution analysts on the proper use of the test data, while limitations identify capability shortfalls in the test configuration. These caveats and limitations are linked to the specific test objectives and test requirements of a given test.

Accreditation

In accordance with MDA policy, all core M&S will be accredited to support acquisition decisions. M&S are abstractions and may not duplicate all actual, observed phenomena; however, they can provide reasonable approximations. Based on V&V activities and integration testing, an assessment is performed to determine the extent to which the HWIL configuration can meet specified test objectives and requirements. Accreditation is the official determination that the test resource provides credible data that can be applied to meet the intended uses within the stated caveats and limitations.

Summary and conclusion

This article articulates how fundamental test objectives can be met for a very complex system of systems, which cannot be evaluated fully through conventional developmental or operational tests. It examines the benefits and challenges of implementing a distributed HWIL to support such assessments using the BMDS as an instance. Areas that are critical in design, implementation, and execution of the BMDS HWIL are addressed. Based on V&V activities and integration testing, an accreditation assessment is performed to determine the extent to which the HWIL configuration can meet specified test objectives and requirements and to establish a degree of confidence in the expected performance. ❑

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